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Continuous particle spectra and their angular distributions

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Abstract : The angular distribution of continuous particle spectra in pre-equilibrium reactions is still an unsolved problem, particularly so at forward angles In the present work, the angular distributions of alpha particles emitted in $(\alpha, \alpha' x)$ reactions in the target elements gold and rhodium have been studied in detail. Alpha particle beams of energy 60 MeV from the Variable Energy Cyclotron of Calcutta were used in these experiments. Self supporting foils of gold (thickness 500 $\mu g/cm^2$) and rhodium (thickness 400 $\mu g/cm^2$) were bombarded by the collimated alpha beams inside a 1 m dia scattering chamber. The emitted alpha particles were identified and detected by ΔE–E detector telescope placed at different angles, in the forward angle region 20° to 60°. The data was stored on a mag-tape on-line event by event in the list mode using ND 560 Computer and was analysed later off-line.

The theoretical calculations were done using an extended exciton model of Kalbach incorporated into the Computer Code PRECO-D2. The formalism used in the exciton model was modified to include division of pre equilibrium cross section into Multi-Step Direct (MSD) and Multi-step Compound (MSC) components. These MSD and MSC cross sections were used to calculate the angular distributions in terms of Legendre polynomials whose coefficients are given by simple phenomenological relations. Even with a reasonable set of parameters, the agreement between theory and experiment was far from satisfactory at forward angles. Similar conclusion was also drawn in the case of continuous particle spectra of deuterons in $(d, d'x)$ reactions at 25 MeV in various targets.

Keywords : Pre-equilibrium reactions, angular distribution of continuous particle spectra, Kalbach's exciton model

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1. Introduction

In light ion induced reactions starting from 10 MeV to a few hundreds of MeV, the emitted particle spectrum shows up a continuous region between the evaporative part and the high energy part which is the so called pre-equilibrium region. It accounts for the ejectiles during the equilibration process between the high energetic projectile and target nucleus system proceeding towards the statistical equlibrium *via* a series of binary collisions. Several pre-equilibrium models based on the exciton picture of Griffin [1] have been formulated [2,3]. Because of their simplicity for use, all existing semiclassical models are extensively used to describe the light ion induced reactions. Later, these models have been extended to include the angular distributions of emitted particles also. Most important of these was the generalised exciton model (GEM) [4,5]. To better reproduce angular distributions at backward angles additional physics has been introduced destroying the simplicity of the exciton model. Also theories based on quantum mechanical methods were formulated [6,7]. The computational difficulties with quantum mechanical models and persistent failure of semi classical models led Kalbach and Mann, [8,9] to approach the problem phenomenologically. Their model has recently been extended to higher energies by Kalbach [10]. In the present work, we studied the angular distributions of deuterons in (d, d') reactions in the target nuclei Nb and Ta, and of alphas in (α, α') reactions in Rh and Au, with a view to compare the results with the theoretical predictions of Kalbach.

2. Experimental procedure

The experiments were carried out at the Variable Energy Cyclotron Centre, Calcutta with alpha particle beam and at the Isochronous cyclotron of Bonn, Germany with deuteron beam. The energies for alpha and deuteron beams were 60 and 25.5 MeV respectively. Since the experimental procedure is same for both the experiments, we will describe for the alpha induced reactions only. The targets were self supporting foils made by vaccum evaporation, with thickness of 500 $\mu g/cm^2$ and 400 $\mu g/cm^2$. The alpha particle beam entering into the 90 cm diameter scattering chamber was restricted to 3 mm diameter by the collimating system. The emitted particles were identified and detected by the two-detector telescope fixed on the telescope housing on the movable arm inside the scattering chamber. The two detectors have thicknesses 300 μm and 5 mm respectively. The total number of alphas striking the target was measured with a faraday cup equipped with a secondary electron suppression device. Signals from the detectors were fed through standard electronics to analog-to-digital convertors and then stored on a magnetic tape on-line in the list mode using ND 560 computer. The data were analysed later, off-line, after sorting. After the final calibration, the data were converted into cross sections. The overall errors in the measurements was nearly 15%. In (α, α') reactions, we restricted ourselves to the forward region 20°–60° with respect to beam axis, and in (d, d') reactions the region upto 160° was covered.

3. Kalbach's model

To account for the shapes of angular distributions, Kalbach took the basic idea of dividing the pre-equilibrium cross section into multi-step direct (MSD) and multi-step compound (MSC) from the work of Feshbach, Kerman and Koonin [7]. She developed a semi-

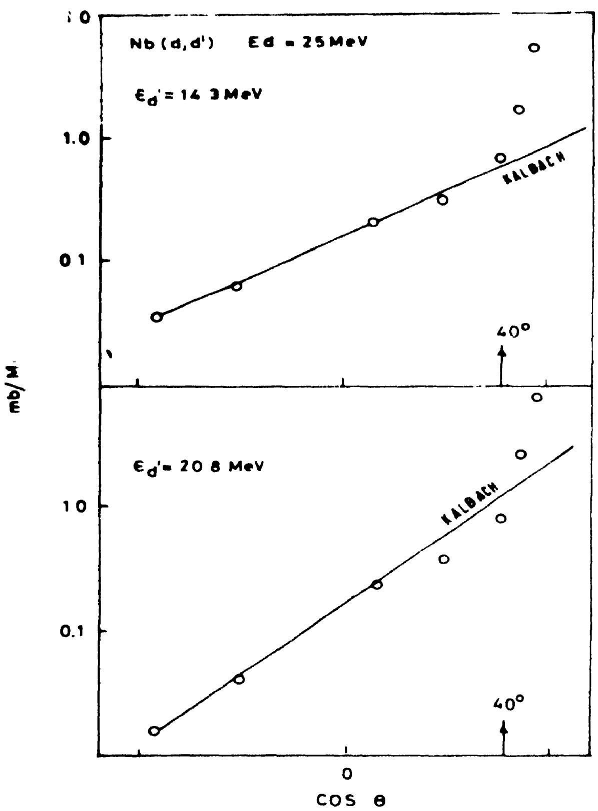

Figure 1. Comparison of experimental values with Kalbach's model in (d, d') reactions in ^{93}Nb

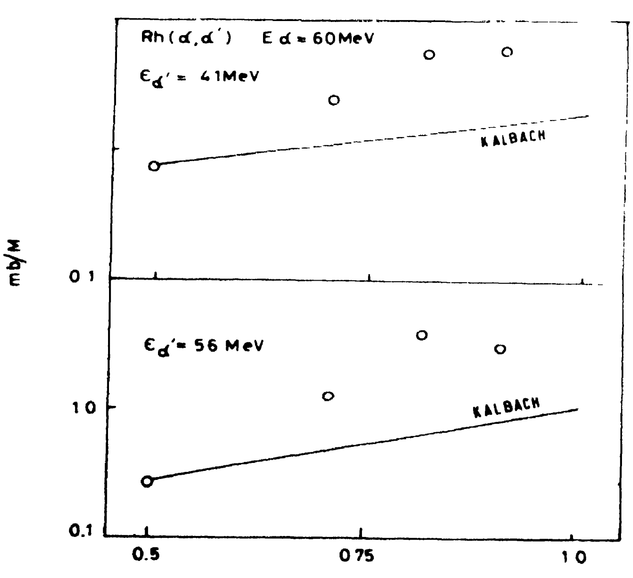

Figure 2. Comparison of experimental values with Kalbach's model in (α, α') reactions in ^{103}Rh.

empirical formula expressing the angular distribution in terms of exponential functions of $\cos\theta$ and the ratio, f_{MSD}, of multistep direct-to-total pre equilibrium cross section :

$$\frac{d^2\sigma}{d\varepsilon d\Omega} \quad \frac{1}{4\pi}\frac{d\sigma}{d\varepsilon}\frac{a}{\sinh a}[\cosh(a\cos\theta)+f_{MSD}\sinh(a\cos\theta)] \tag{1}$$

where a is a slope parameter to be explained later. For bombarding energies above a few tens of MeV, $f_{MSD} \approx 1$ and eqn. (1) effectively reduces to

$$\frac{d^2\sigma}{d\varepsilon d\Omega} = \frac{1}{4\pi}\frac{d\sigma}{d\varepsilon}\frac{a}{\sinh a}\exp(a\cos\theta) \tag{2}$$

A plot between ln $d^2\sigma / d\varepsilon\, d\Omega$ and $\cos\theta$ thus gives a straight line with the slope given by a. Kalbach assumed the dependence of a on ejectile energy ε only, and gave an empirical formula to calculate it :

$$a = 0.040\, e + 1.8 \times 10^{-6}\, (e)^3$$

where $e = \varepsilon + B$, B being the binding energy of the emitted particle.

4. Results and conclusion

Figures 1 and 2 show the comparison between the experimental angular distributions and the predictions of Kalbach's model, for Nb (d, d') and Rh (α, α') reactions typically. It can be seen from Figure 1 that while there is fair agreement for backward angles from 180° to 40°, large deviations do occur for smaller scattering angles. The results of Rh (α, α') reactions, studied in detail at forward angles upto 60° shown in Figure 2, confirm the failure of Kalbach's semi-empirical model, calling for a more sophisticated theory to describe the angular distributions at forward angles.

References

[1] J J Griffin *Phys. Rev. Lett.* **17** 478 (1966)

[2] M Blann *Ann. Rev. Nucl.Sci.* **25** 123 (1975)

[3] H Machner *Phy. Rep.* **127** 309 (1985)

[4] G Mountzouranis, W A Weidenmuller and D Agassi *Z. Phys.* **A276** (1976); G Mountzouranis *Phys. Rev.* **C14** 2018 (1976)

[5] J M Akkermans *Phys. Lett.* **82B** 20 (1979); J M Akkermans, H Gruppelaar and G Reffo *Phys. Rev.* **C22** 73 (1980)

[6] T Tamura, T Udagawa, D H Feng and K K Kan *Phys. Lett.* **66B** 109 (1977)

[7] H Feshbach, A Kerman and K Koonin *Ann. Phys.* **125** 429 (1980)

[8] C Kalbach and F M Mann *Phys. Rev.* **C23** 112 (1981)

[9] C Kalbach *Phys. Rev.* **C23** 124 (1981)

[10] C Kalbach *Phys. Rev.* **C37** 2350 (1988)